

All Possible Lightest Supersymmetric Particles in R-Parity Violating Minimal Supergravity Models [☆]

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Abstract

We investigate, which lightest supersymmetric particles can be obtained via a non-vanishing lepton- or baryon-number violating operator at the grand unification scale within the R-parity violating minimal supergravity model. We employ the full one-loop renormalization group equations. We take into account restrictions from the anomalous magnetic moment of the muon and $b \rightarrow s\gamma$, as well as collider constraints from LEP and the Tevatron. We also consider simple deformations of minimal supergravity models.

Key words: Renormalization group, mSUGRA, R-parity violation, Lightest supersymmetric particle

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1. Introduction

In the minimal supersymmetric Standard Model (MSSM) [1], the lightest supersymmetric particle (LSP) is stable, guaranteed by the discrete symmetry proton hexality, P_6 [2] or R-parity [3]. This also ensures the stability of the proton. For cosmological reasons the LSP must then be the lightest neutralino [4, 5] and it has been widely studied as a very promising cold dark matter candidate [6]. However, if we drop P_6 then there are further renormalizable interaction operators in the superpotential [7]

$$\begin{aligned}
 W_{\mathcal{P}_6} = & \epsilon_{ab} \left[\frac{1}{2} \lambda_{ijk} L_i^a L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a Q_j^b \bar{D}_{kx} \right] \\
 & + \epsilon_{ab} \kappa^i L_i^a H_u^b + \frac{1}{2} \epsilon_{xyz} \lambda''_{ijk} \bar{U}_i^x \bar{D}_j^y \bar{D}_k^z .
 \end{aligned} \tag{1}$$

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In order to ensure the stability of the proton, we must prohibit either the first three set of terms which violate lepton-number, or the last set of terms which violate baryon-number.¹ These terms violate \mathcal{P}_6 (\mathcal{P}_6) and thus the LSP is no longer stable. It is then also not restricted to be the lightest neutralino and can in principle be any supersymmetric (SUSY) particle [3]

$$\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\ell}_{L/Ri}^\pm, \tilde{\tau}_1, \tilde{\nu}_i, \tilde{q}_{L/Rj}, \tilde{b}_1, \tilde{t}_1, \tilde{g}. \quad (2)$$

Here we have the lightest neutralino and chargino ($\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$), a left-/right-handed charged slepton ($\tilde{\ell}_{L/Ri}^\pm$, $i = 1, 2$), a sneutrino ($\tilde{\nu}_i$, $i = 1, 2, 3$), a left-/right-handed squark ($\tilde{q}_{L/Rj}$, $j = 1, 2$), and a gluino (\tilde{g}). We have separately listed the lightest stau $\tilde{\tau}_1$, sbottom \tilde{b}_1 , and stop \tilde{t}_1 , as they have possibly large Yukawa couplings and left-right mixing and are thus promising LSP candidates. Potential other dark matter candidates are the axino [10], the gravitino [11] and the lightest U-parity particle [8, 9, 12].

In the search for supersymmetry at colliders, it is essential to know the nature of the LSP, because SUSY particles, if produced, normally cascade decay down to the LSP within the detector. The LSP then decays promptly or with a detached vertex if \mathcal{P}_6 is violated. It is thus a central ingredient of almost all SUSY signatures.

In Eq. (2), we have a bewildering array of potential LSPs. We thus need a guiding principle in order to perform a systematic phenomenological analysis. A well motivated restricted framework for detailed studies of the MSSM is minimal supergravity (mSUGRA) [1]. The 124 free MSSM parameters are reduced to only five,

$$M_0, M_{1/2}, A_0, \tan\beta, \text{sgn}(\mu), \quad (3)$$

where M_0 ($M_{1/2}$) is the universal supersymmetry breaking scalar (gaugino) mass and A_0 is the universal supersymmetry breaking trilinear scalar interaction; all given at the grand unification (GUT) scale: M_{GUT} . $\tan\beta$ is the ratio of the two vacuum expectation values and μ is the Higgs mixing parameter. We obtain the masses of the SUSY particles (sparticles) by running the renormalization group equations (RGEs) for the SUSY parameters, from M_{GUT} to the electroweak scale M_Z using **SOFTSUSY** [13]. In most of the mSUGRA parameter space the $\tilde{\chi}_1^0$ or the $\tilde{\tau}_1$, is the LSP [7, 14, 15].

In Ref. [7] the \mathcal{P}_6 effects were taken into account in the RGEs: giving the \mathcal{P}_6 mSUGRA model. Here, one additional coupling beyond Eq. (3) is assumed:

$$\Lambda \in \{\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}\} \quad \text{at } M_{\text{GUT}}. \quad (4)$$

We thus have a simple well-motivated framework, in which we can systematically investigate the nature of the LSP. It is the purpose of this letter to determine all possible LSPs in the \mathcal{P}_6 mSUGRA model. We also briefly discuss simple deformations of mSUGRA. This is very important for SUSY searches at the LHC.

¹See also Refs. [8, 9] for a $U(1)'$ solution to the proton decay problem with R-parity violation.

2. Non- $\tilde{\chi}_1^0$ LSP parameter space of mSUGRA models

If a sparticle directly couples to the operator corresponding to $\mathbf{\Lambda}$, the dominant contributions to the RGE of the running sparticle mass \tilde{m} are [7, 16]:²

$$16\pi^2 \frac{d(\tilde{m}^2)}{dt} = -a_i g_i^2 M_i^2 - b g_1^2 \mathcal{S} + \mathbf{\Lambda}^2 \mathcal{F} + c \mathbf{h}_{\mathbf{\Lambda}}^2, \quad (5)$$

$$\mathbf{h}_{\mathbf{\Lambda}} \equiv \mathbf{\Lambda} \times A_0 \quad \text{at } M_{\text{GUT}}. \quad (6)$$

Here $g_i (M_i)$, $i = 1, 2, 3$, are the gauge couplings (soft breaking gaugino masses). $t = \ln Q$ with Q the renormalization scale and a_i, b, c are constants of $\mathcal{O}(10^{-1} - 10^1)$. \mathcal{S} and \mathcal{F} are linear functions of products of two softbreaking scalar masses and are given explicitly in Refs. [7, 16].

coupling $\mathbf{\Lambda}$	LSP	coupling $\mathbf{\Lambda}$	LSP
λ_{132}	$\tilde{\mu}_R$	$\lambda_{121}, \lambda_{131}, \lambda_{231}$	\tilde{e}_R
λ'_{ijk}	$\tilde{\nu}_i$	λ''_{212}	$\tilde{s}_R / \tilde{d}_R$
$\lambda''_{123}, \lambda''_{213}, \lambda''_{223}$	\tilde{b}_1	λ''_{323}	\tilde{t}_1

Table 1: All possible non- $\tilde{\chi}_1^0$ (and non- $\tilde{\tau}_1$) LSP candidates in \mathcal{P}_6 mSUGRA via a non-vanishing $\mathbf{\Lambda} = \mathcal{O}(10^{-1})$, consistent with the experimental bounds, cf. Refs. [3, 18].

The sum of the first two \mathcal{P}_6 -conserving terms in Eq. (5) is negative and thus *increases* \tilde{m} when running from M_{GUT} to M_Z . In contrast, the last two \mathcal{P}_6 terms proportional to $\mathbf{\Lambda}^2$, and $\mathbf{h}_{\mathbf{\Lambda}}^2$, are always positive and therefore *decrease* \tilde{m} . We thus expect new LSP candidates beyond $\tilde{\chi}_1^0$, and $\tilde{\tau}_1$ if these latter terms contribute substantially. As we shall see below, this is the case if $\mathbf{\Lambda} = \mathcal{O}(10^{-1})$, *i.e.* $\mathbf{\Lambda} = \mathcal{O}(g_i)$ [16]. We can strengthen the (negative) contribution of $\mathbf{h}_{\mathbf{\Lambda}}^2$, by choosing a negative A_0 with a large magnitude; for moderate positive A_0 there is a cancellation in the RGE evolution of $\mathbf{h}_{\mathbf{\Lambda}}$ [16]. The other terms are not significantly affected by A_0 . Note that we also need $M_{1/2}(\tan\beta)$ large (small) enough to avoid a $\tilde{\chi}_1^0$ ($\tilde{\tau}_1$) LSP.

We now investigate the non- $\tilde{\chi}_1^0$ LSP parameter space of \mathcal{P}_6 mSUGRA, *i.e.* with one non-vanishing \mathcal{P}_6 coupling $\mathbf{\Lambda} = \mathcal{O}(10^{-1})$. We discuss the obtainable LSPs for the various \mathcal{P}_6 -operators. We shall focus here on the $LL\bar{E}$ and $\bar{U}\bar{D}\bar{D}$ operators. In previous work in Refs. [7, 14, 16] it was shown that $\lambda'_{ijk}|_{\text{GUT}} = \mathcal{O}(10^{-1})$ can lead to a $\tilde{\nu}_i$ LSP. In general $LQ\bar{D}$ operators can only lead to a $\tilde{\nu}_i$ LSP beyond a $\tilde{\chi}_1^0$ or a $\tilde{\tau}_1$, in \mathcal{P}_6 mSUGRA. We thus refer to Ref. [16] for a discussion of the $\tilde{\nu}_i$ LSP via $\lambda'_{ijk}|_{\text{GUT}} \neq 0$. We also note that Ref. [7, 17] gives the example of an \tilde{e}_R LSP via $\lambda_{231}|_{\text{GUT}} = \mathcal{O}(10^{-1})$.

In searching for LSP candidates, we take into account the constraints from the decay $b \rightarrow s\gamma$ [19], as well as the anomalous magnetic moment of the muon [20]. In the figures, we show (dashed yellow) contour lines corresponding to the 2σ window for the $\text{BR}(b \rightarrow s\gamma)$ [19],

$$2.74 \times 10^{-4} < \text{BR}(b \rightarrow s\gamma) < 4.30 \times 10^{-4}, \quad (7)$$

²For third generation sparticles we also need to take into account the contributions from the Higgs-Yukawa interactions. Their effect is similar to $\mathbf{\Lambda}$ and $\mathbf{h}_{\mathbf{\Lambda}}$ in Eq. (5), see Ref. [7].

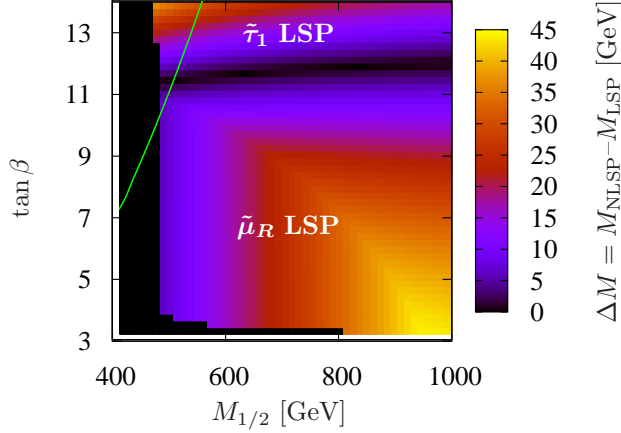


Figure 1: Mass difference, ΔM , between the NLSP and LSP. The LSP candidates are explicitly mentioned in the plot. The blackened out region on the left and bottom corresponds to parameter points, which possess a tachyon or which violate other constraints as described in the text. The contour line is described in the text. The other mSUGRA parameters are $\lambda_{132}|_{\text{GUT}} = 0.09$, $M_0 = 170$ GeV, $A_0 = -1500$ GeV and $\text{sgn}(\mu) = +1$.

and (solid green) contour lines corresponding to the 2σ window for the SUSY contributions to the anomalous magnetic moment of the muon [20]

$$11.9 \times 10^{-10} < \delta a_\mu^{\text{SUSY}} < 47.1 \times 10^{-10}. \quad (8)$$

See also Ref. [16] and references therein. We employ the LEP exclusion bound on the light Higgs mass [21], but we reduce it by 3 GeV to $m_h > 111.4$ GeV, to account for numerical uncertainties of SOFTSUSY [14, 22]. We use microOMEGAS1.3.7 [23] to calculate $\text{BR}(b \rightarrow s\gamma)$ and $\delta a_\mu^{\text{SUSY}}$.

Our results are summarized in Table 1 and are explained in the following. We only consider operators for which $\mathbf{\Lambda} = \mathcal{O}(10^{-1})$ is consistent with existing experimental bounds [3, 18]. We argue that Table 1 gives a complete list of all possible non- $\tilde{\chi}_1^0$ and non- $\tilde{\tau}_1$ LSP candidates in \mathcal{P}_6 mSUGRA. In Sect. 3 below, we shall also consider simple deformations of \mathcal{P}_6 mSUGRA.

2.1. Non- $\tilde{\chi}_1^0$ LSPs via LLE

The least constrained couplings of the $L_i L_j \bar{E}_k$ operators, Eq. (1), are [3, 7, 18]

$$\begin{aligned} \lambda_{121}, \lambda_{131} &< 0.15, & \lambda_{123} &< 0.05 \times (m_{\tilde{\tau}_R}/100 \text{ GeV}), \\ \lambda_{132}, \lambda_{231} &< 0.07 \times (m_{\tilde{\mu}_R, \tilde{e}_R}/100 \text{ GeV}), \end{aligned} \quad (9)$$

where the bounds apply at M_Z . Note, that λ_{ijk} is reduced by roughly a factor of 1.5 when running from M_Z to M_{GUT} [18]. There is no scaling factor for the first bound as it is derived from the neutrino mass bound via the RGEs [7].

We give in Fig. 1 the $\tilde{\mu}_R$ LSP region in the $M_{1/2}$ - $\tan\beta$ plane for a λ_{132} -coupling. We show the mass difference, ΔM , between the NLSP and LSP. We have employed a lower bound of 190 GeV on the $\tilde{\mu}_R$ mass to fulfill the strong bound on λ_{132} . The remaining SUSY particles are then so heavy

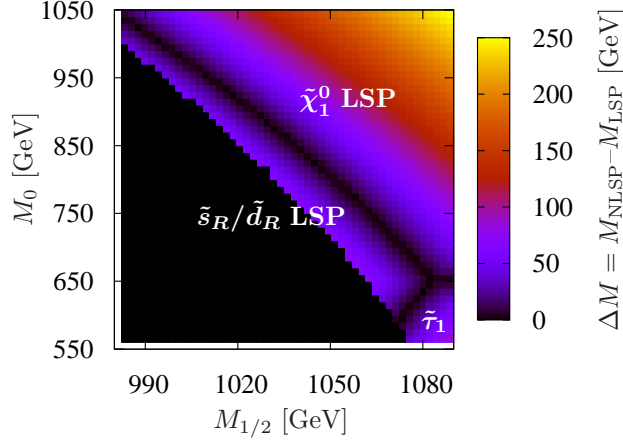


Figure 2: Same as Fig. 1, but with $\lambda''_{212}|_{\text{GUT}} = 0.5$, $A_0 = -3700$ GeV, $\tan \beta = 19$ and $\text{sgn}(\mu) = +1$.

within \mathcal{P}_6 mSUGRA, that other collider constraints from LEP and the Tevatron are automatically fulfilled.

We see that the $\tilde{\mu}_R$ LSP exists in an extended region of \mathcal{P}_6 mSUGRA. We find a $\tilde{\mu}_R$ LSP for all $M_{1/2} > 480$ GeV, because $M_{1/2}$ increases the mass of the (bino-like) $\tilde{\chi}_1^0$ faster than the mass of the $\tilde{\mu}_R$ [16]. The complete $\tilde{\mu}_R$ LSP region in Fig. 1 agrees with $\text{BR}(b \rightarrow s\gamma)$ at 2σ . But only a tiny region is consistent with $\delta a_\mu^{\text{SUSY}}$ at 2σ , *i.e.* lies above the solid green line. The mass spectra are rather heavy and thus $\delta a_\mu^{\text{SUSY}}$ is suppressed.

If we use λ_{231} , λ_{121} or λ_{131} instead of λ_{132} in our parameter scans, we obtain a \tilde{e}_R as the LSP. We can not obtain a $\tilde{\ell}_L$ as the LSP in \mathcal{P}_6 mSUGRA with $\lambda|_{\text{GUT}} \neq 0$. On the one hand, the \mathcal{P}_6 -conserving contributions to the RGEs of $m_{\tilde{\ell}_L}^2$ have a larger magnitude compared to those for $m_{\tilde{\ell}_R}^2$. On the other hand, the (negative) \mathcal{P}_6 contributions to $m_{\tilde{\ell}_L}^2$ are smaller in magnitude compared to those for $m_{\tilde{\ell}_R}^2$ [7].

2.2. Non- $\tilde{\chi}_1^0$ LSPs via UDD

The following baryon-number violating couplings, λ''_{ijk} , are only constrained by perturbativity [3, 18, 24]

$$\lambda''_{212}, \lambda''_{123}, \lambda''_{213}, \lambda''_{223}, \lambda''_{323} \lesssim \mathcal{O}(1). \quad (10)$$

The corresponding operators only affect SU(2) singlet squarks directly, we can thus only obtain \tilde{q}_R LSPs via these λ''_{ijk} couplings.

We assume that the weak- and mass-eigenstates of *right*-handed quarks are the same [25]. With this assumption we avoid the RGE generation of additional couplings λ''_{lmn} at M_Z out of $\lambda''_{ijk}|_{\text{GUT}}$, which might be in contradiction with experiment [3, 18]. We have also checked that there are then no new \mathcal{P}_6 contributions (at one-loop) in the RGEs which generate off-diagonal squark mass matrix elements. The right-handed squark weak-eigenstates are therefore approximately equal to their mass eigenstates at M_Z . We thus avoid large flavour changing neutral currents. Note that we only have experimental information about mixing in the left-handed quark sector (CKM matrix).

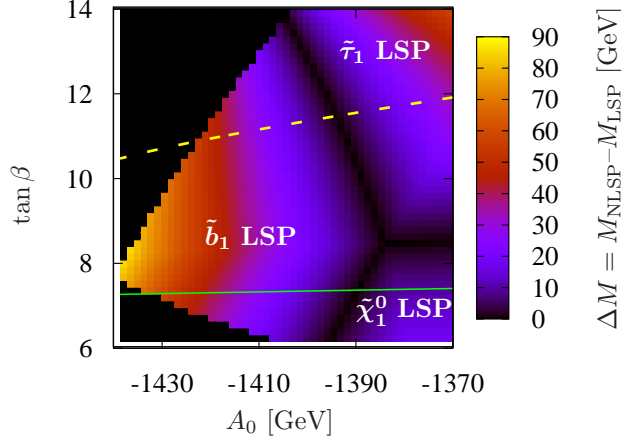


Figure 3: Same as Fig. 1, but with $\lambda''_{223}|_{\text{GUT}} = 0.5$, $M_0 = 120$ GeV, $M_{1/2} = 400$ GeV and $\text{sgn}(\mu) = +1$.

We show in Fig. 2 the \tilde{d}_R/\tilde{s}_R LSP region via $\lambda''_{212}|_{\text{GUT}} = 0.5$ in the $M_{1/2}$ - M_0 plane. The \tilde{d}_R and \tilde{s}_R are degenerate in mass, because both particles interact the same via the gauge interactions and via λ''_{212} [7]. We conservatively impose a lower bound of 380 GeV on the \tilde{d}_R/\tilde{s}_R mass, consistent with the non-observation of the \tilde{d}_R/\tilde{s}_R in resonance searches in the dijet channel at the Tevatron [26].³

We can not get a \tilde{c}_R LSP via $\lambda''_{212}|_{\text{GUT}} \neq 0$. The \mathcal{P}_6 contributions to the RGEs of the \tilde{d}_R , \tilde{s}_R and \tilde{c}_R mass are the same. But the \tilde{c}_R couples stronger to the U(1) gaugino than the \tilde{d}_R and \tilde{s}_R and is therefore always heavier than \tilde{d}_R and \tilde{s}_R .⁴ For example, the \tilde{c}_R in Fig. 2 is roughly 60 GeV heavier than the \tilde{d}_R/\tilde{s}_R .

Due to $m_{\tilde{d}_R/\tilde{s}_R} > 380$ GeV, we need $M_{1/2} = \mathcal{O}(1 \text{ TeV})$, as can be seen in Fig. 2, to obtain also a heavy $\tilde{\chi}_1^0$. This results in such a heavy mass spectrum that $\delta a_\mu^{\text{SUSY}}$ lies beyond the experimental 2σ window. However the complete \tilde{d}_R/\tilde{s}_R LSP region in Fig. 2 is consistent with $\text{BR}(b \rightarrow s\gamma)$ at 1σ .

Only small $M_{1/2}$ intervals are allowed in Fig. 2, because $m_{\tilde{d}_R/\tilde{s}_R}$ at M_Z increases very rapidly with increasing $M_{1/2}$. The dependence on M_0 is weaker, *i.e.* M_0 intervals up to 100 GeV (for constant $M_{1/2}$) are allowed in Fig. 2. These are general features of most of the squark LSP regions. We thus concentrate on A_0 and $\tan\beta$ in what follows. $\tan\beta$ is important, because increasing $\tan\beta$ increases [decreases] $\delta a_\mu^{\text{SUSY}}$ [$\text{BR}(b \rightarrow s\gamma)$], *cf.* Ref. [14].

We give in Fig. 3 the \tilde{b}_1 LSP region via $\lambda''_{223}|_{\text{GUT}} = 0.5$ in the A_0 - $\tan\beta$ plane. The \tilde{b}_1 LSP mass lies between 77 GeV and 180 GeV. The lower value corresponds to the strongest LEP bound [27]. Note, that there is no bound on the \tilde{b}_1 LSP mass from Tevatron searches. The single \tilde{b}_1 production

³It is not clear if Ref. [26] can exclude $m_{\tilde{d}_R/\tilde{s}_R} < 380$ GeV. They did not search for single squark resonances. A more detailed analysis is required, including NLO corrections to single \tilde{d}_R/\tilde{s}_R production.

⁴The \tilde{c}_R can in principle be lighter than the \tilde{d}_R and \tilde{s}_R if $M_{1/2} \lesssim 200$ GeV due to different D-term contributions. However, the \tilde{c}_R LSP parameter space is in that case excluded by constraints from LEP [27, 21].

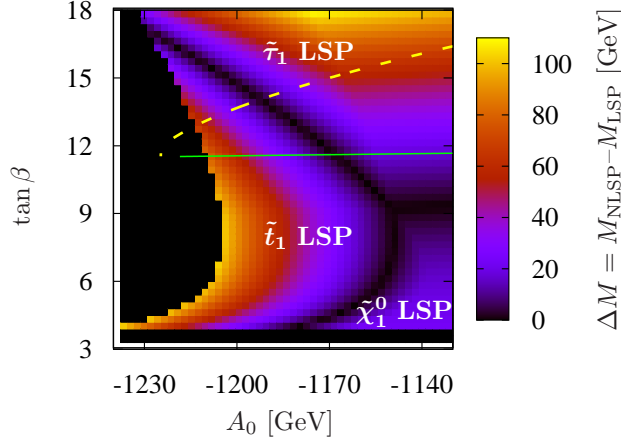


Figure 4: Same as Fig. 1, but with $\lambda''_{323}|_{\text{GUT}} = 0.35$, $M_0 = 120$ GeV, $M_{1/2} = 480$ GeV and $\text{sgn}(\mu) = +1$.

cross section via $\lambda''_{223}|_{\text{GUT}} = 0.5$ lies below the exclusion limits for a dijet resonance, *cf.* Ref. [26], due to the small incoming parton luminosity.

Most of the \tilde{b}_1 LSP region in Fig. 3 is also consistent with $\text{BR}(b \rightarrow s\gamma)$ (below the upper dashed yellow line) and $\delta a_\mu^{\text{SUSY}}$ (above the lower solid green line) at the 2σ level. We observe that $A_0 = \mathcal{O}(-1 \text{ TeV})$ is vital to obtain a \tilde{b}_1 LSP. Increasing A_0 , *i.e.* decreasing the magnitude, reduces the (negative) effect of $\lambda''_{223}|_{\text{GUT}}$ on the running of the \tilde{b}_1 mass and we re-obtain the $\tilde{\chi}_1^0$ or $\tilde{\tau}_1$ LSP, *cf.* Ref [16].

We can also obtain a \tilde{b}_1 LSP, if we use $\lambda''_{123}|_{\text{GUT}}, \lambda''_{213}|_{\text{GUT}} \neq 0$. But now there might be additional constraints from the Tevatron on di-jet resonances [26]. The couplings λ''_{123} and λ''_{213} unlike λ''_{223} allow for single \tilde{b}_1 production via a valence quark or antiquark, which enhances the hadronic cross section. Note, that these three couplings can only lead to a \tilde{b}_1 LSP, because the \tilde{b}_1 mass (compared to the \tilde{q}_R masses of the first two generations) is further reduced by the large bottom Yukawa coupling and by larger left-right mixing.

For $\lambda''_{323}|_{\text{GUT}} = 0.35$, we obtain a \tilde{t}_1 LSP as shown in Fig. 4 for the A_0 - $\tan\beta$ plane. The \tilde{t}_1 LSP mass ranges from 94 GeV to 200 GeV. The lower bound corresponds to the LEP bound on $m_{\tilde{t}_1}$ [27].⁵ The \tilde{t}_1 LSP region below the upper dashed yellow line [above the solid green line] is also consistent with $\text{BR}(b \rightarrow s\gamma)$ [$\delta a_\mu^{\text{SUSY}}$] at 2σ .

We need in general a smaller coupling $\lambda''_{ijk}|_{\text{GUT}}$ to obtain a \tilde{t}_1 LSP than \tilde{b}_1 LSP, because the \tilde{t}_1 mass is further reduced by the large top Yukawa coupling. This effect is enhanced by a negative A_0 with a large magnitude. $A_0 = \mathcal{O}(-1 \text{ TeV})$ also leads to large left-right mixing, which further reduces the \tilde{t}_1 mass. For the same reasons we can not obtain another squark LSP than the \tilde{t}_1 via $\lambda''_{323}|_{\text{GUT}} \neq 0$.

The complete \tilde{t}_1 LSP region in Fig. 4 should be testable at the Tevatron [28]. (See also Ref. [29].) The authors found that \tilde{t}_1 masses up to 190 GeV (210 GeV) can probably be explored at the

⁵Unlike the b_1 LSP, the \tilde{t}_1 LSP has a large left-handed component due to left-right mixing. As a conservative approach, we take the (stronger) mass bounds from Ref. [27] for purely left-handed up-type squarks.

scenario	universal masses	non-universal masses	LSP
1	$M_0 = 1500 \text{ GeV}, M_{1/2} = 2000 \text{ GeV},$ $A_0 = 800 \text{ GeV}, \tan \beta = 10, \text{sgn}(\mu)=+1$	$M_3 = 300 \text{ GeV}$	\tilde{g}
2	$M_0 = 180 \text{ GeV}, M_{1/2} = 1000 \text{ GeV},$ $A_0 = -900 \text{ GeV}, \tan \beta = 10, \text{sgn}(\mu)=+1$	$M_3 = 400 \text{ GeV}$	\tilde{t}_1
3	$M_0 = 100 \text{ GeV}, M_{1/2} = 500 \text{ GeV},$ $A_0 = 0 \text{ GeV}, \tan \beta = 10, \text{sgn}(\mu)=+1$	$M_{\tilde{E}1} = 0 \text{ GeV}$	\tilde{e}_R
4	$M_0 = 500 \text{ GeV}, M_{1/2} = 600 \text{ GeV},$ $A_0 = 200 \text{ GeV}, \tan \beta = 20, \text{sgn}(\mu)=+1$	$M_1 = 1300 \text{ GeV},$ $M_{\tilde{L}1} = M_{\tilde{L}2} = M_{\tilde{L}3} = 0 \text{ GeV}$	$\tilde{\nu}_\tau$
5	$M_0 = 1000 \text{ GeV}, M_{1/2} = 1000 \text{ GeV},$ $A_0 = -800 \text{ GeV}, \tan \beta = 40, \text{sgn}(\mu)=+1$	$M_3 = 300 \text{ GeV},$ $M_{\tilde{D}1} = M_{\tilde{D}2} = M_{\tilde{D}3} = 0 \text{ GeV}$	\tilde{b}_1
6	$M_0 = 1300 \text{ GeV}, M_{1/2} = 1100 \text{ GeV},$ $A_0 = 400 \text{ GeV}, \tan \beta = 30, \text{sgn}(\mu)=+1$	$M_3 = 180 \text{ GeV},$ $M_{\tilde{D}1} = 0 \text{ GeV}$	\tilde{d}_R
7	$M_0 = 400 \text{ GeV}, M_{1/2} = 400 \text{ GeV},$ $A_0 = -1200 \text{ GeV}, \tan \beta = 15, \text{sgn}(\mu)=+1$	$M_{H_u}^2 = 1150^2 \text{ GeV}^2$	\tilde{t}_1

Table 2: Examples for LSP candidates in simple deformations of mSUGRA in 7 different scenarios. The second column shows the universal soft breaking masses at M_{GUT} . We give in the third column the non-mSUGRA soft breaking masses at M_{GUT} which deviate from the boundary conditions in the second column. In particular, we show the masses of the bino M_1 , the gluino M_3 , the right-handed selectron $M_{\tilde{E}1}$, the left-handed sleptons $M_{\tilde{L}i}$, the right-handed down-type squarks $M_{\tilde{D}i}$, and the up-type Higgs M_{H_u} . We assume the effect of Λ , Eq. (4), to be negligible, *i.e.* $\Lambda \lesssim \mathcal{O}(10^{-2})$.

Tevatron for an integrated luminosity of 2 fb^{-1} (8 fb^{-1}). However, this analysis has not yet been performed by the Tevatron collaborations.

3. LSP candidates in simple deformations of mSUGRA

Up to now, we have considered the restricted framework of \mathcal{P}_6 mSUGRA. In this section, we want to briefly comment on how the nature of the LSP can change when we relax some of the mSUGRA boundary conditions, Eqs. (3) and (4). Throughout this section, we assume that Λ , Eq. (4), is $\lesssim \mathcal{O}(10^{-2})$. \mathcal{P}_6 terms then have no significant impact on the RGE running of the sparticle masses, *cf.* Eq. (5). We thus effectively explore the various corners of deformed, \mathcal{P}_6 -conserved mSUGRA parameter space. This has hitherto not been done, since it leads to cosmologically not viable LSPs in the \mathcal{P}_6 case. The additional effects on the low-energy mass spectrum of the \mathcal{P}_6 -operators for larger Λ have been discussed in the previous sections, and apply here correspondingly. In Table 2, we give examples for the scenarios which we now discuss.

First, we consider non-universal gaugino masses, *i.e.* $M_1 \neq M_2 \neq M_3$ at M_{GUT} . Here, M_1 , M_2 , and M_3 are the masses of the bino, the winos, and the gluinos, respectively. For $M_3 \ll M_1, M_2$ at M_{GUT} , we can obtain a \tilde{g} LSP if the scalar sparticles and the $\tilde{\chi}_1^0$ are heavy enough, *i.e.* if M_0 , M_1 , and M_2 are large enough. As an example, we present scenario 1 in Table 2. If we reduce M_0 but maintain $M_3 \ll M_1, M_2$, we get a \tilde{t}_1 as the LSP, see scenario 2. The squarks are relatively light for small M_3 and M_0 . The \tilde{t}_1 mass is further reduced by the effect of the large top Yukawa coupling

on the running and due to left-right mixing. For $M_2 \ll M_1$ at M_{GUT} , we can get a wino-like $\tilde{\chi}_1^0$ LSP (instead of a bino-like $\tilde{\chi}_1^0$ as in mSUGRA) which is nearly degenerate in mass with the $\tilde{\chi}_1^+$. A $\tilde{\chi}_1^+$ LSP is in principle possible but difficult to obtain, see Ref. [30] for details.

Next, we consider non-universal sfermion masses at M_{GUT} . For small right-handed slepton soft breaking masses, $M_{\tilde{E}_i}$, we can obtain a \tilde{e}_R or a $\tilde{\mu}_R$ LSP (beyond the $\tilde{\tau}_1$ LSP in mSUGRA) if $M_{1/2}$ is large enough, scenario 3. For small left-handed slepton soft breaking masses, $M_{\tilde{L}_i}$, and $M_2 \ll M_1$, we can get a $\tilde{\nu}_i$ LSP. We show the example of a $\tilde{\nu}_\tau$ LSP scenario in Table 2 (scenario 4). A $\tilde{\ell}_{Li}$ LSP is not possible, because it is always heavier than the $\tilde{\nu}_i$ due to the different D-terms [16]. $M_2 \ll M_1$ is vital for the $\tilde{\nu}_i$ to be the LSP, because $M_{\tilde{L}_i}$ increases faster with M_2 than the $\tilde{\chi}_1^0$ mass with M_1 . Finally, squark LSPs are possible for small and non-universal squark soft breaking parameters and $M_3 \ll M_1, M_2$. In these scenarios a \tilde{t}_1 and \tilde{b}_1 LSP is preferred, because their masses are additionally reduced by large Yukawa couplings affecting the RGE running and by left-right mixing; see scenario 5 in Table 2. We obtain non- \tilde{t}_1 and non- \tilde{b}_1 squark-LSPs, if we assume non-universal masses for different squark flavours, *cf.* scenario 6 with a \tilde{d}_R LSP.

Choosing soft breaking Higgs mass parameters different from the universal scalar mass M_0 has the following impact on the sparticle mass spectrum. On the one hand, the RGE running of third generation masses is affected due to terms proportional to the Higgs-Yukawa couplings. We then obtain, for example, a \tilde{t}_1 LSP, *cf.* scenario 7 in Tab. 2. On the other hand, the Higgs mixing parameter μ and the physical Higgs masses can be changed. If μ is small we can get a Higgsino-like $\tilde{\chi}_1^0$ LSP. Note that μ depends on the Higgs soft breaking masses via radiative electroweak symmetry breaking [31].

The mass spectra of the scenarios described above can significantly change if a large \mathcal{P}_6 coupling is present at M_{GUT} , *i.e.* $\Lambda = \mathcal{O}(10^{-1})$. The masses are then modified according to the discussion in the previous sections. For example, if we assume in scenario 2 in Tab. 2 an additional \mathcal{P}_6 coupling $\lambda_{132}|_{\text{GUT}} = 0.14$, we obtain a scenario with a $\tilde{\mu}_R$ LSP, *cf.* Sect. 2.1, and a \tilde{t}_1 as the NLSP.

4. Conclusion

We have investigated for the first time all possible non- $\tilde{\chi}_1^0$ and non- $\tilde{\tau}_1$ LSPs in R-parity violating mSUGRA models; see Table 1. We found that a non-vanishing $L_i L_j \tilde{E}_k$ operator at the GUT scale can lead to a \tilde{e}_R ($i = 1$) or $\tilde{\mu}_R$ ($i = 2$) LSP; *cf.* Fig. 1. A non-vanishing $L_i Q_j \tilde{D}_k$ operator can lead to a $\tilde{\nu}_i$ LSP; *cf.* Ref. [16]. We can also obtain squark LSPs, namely the \tilde{s}_R , \tilde{d}_R , \tilde{b}_1 and \tilde{t}_1 via a non-vanishing $\tilde{U}_i \tilde{D}_j \tilde{D}_k$ operator; see Fig. 2, Fig. 3 and Fig. 4, respectively. We found $\tilde{\mu}_R$, $\tilde{\nu}_i$, \tilde{b}_1 and \tilde{t}_1 LSP scenarios consistent with the observed anomalous magnetic moment of the muon. All LSP candidates found here can be consistent with $b \rightarrow s\gamma$ as well as with collider constraints from LEP and the Tevatron. According to Ref. [28], \tilde{t}_1 LSPs up to a mass of 190 GeV can be tested at the Tevatron with 2 fb^{-1} of data. We therefore want to encourage the Tevatron collaborations to investigate the \tilde{t}_1 LSP parameter space of R-parity violating mSUGRA, as well as to look for squark LSP resonances in dijet events.

We have also discussed simple deformations of mSUGRA; see Tab. 2 for explicit examples. We have first assumed that the R-parity violating coupling at the GUT scale is small, *i.e.* $\Lambda \lesssim \mathcal{O}(10^{-2})$. We have found scenarios with a \tilde{g} and \tilde{t}_1 LSP if $M_3 \ll M_1, M_2$. We can obtain a $\tilde{\ell}_R$ LSP for small right-handed slepton (soft breaking) masses. A $\tilde{\nu}_i$ LSP is possible for small left-handed slepton masses as long as $M_2 \ll M_1$. These scenarios will be significantly affected by R-parity violating terms in the RGEs when $\Lambda = \mathcal{O}(10^{-1})$ as described in Sect. 2.

Due to the simplicity of the framework, we have in this first study restricted ourselves mainly to the mSUGRA case. It would be interesting to extend this work to other supersymmetry breaking models such as gauge mediation [32] or anomaly mediation [33].

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